Modelling and preliminary evaluation of energy savings for a SHC plant in a real application: Misericordia of Badia a Ripoli

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Abstract

Until today, there is a lack in the global market of small scale units, fully automated and autonomous package-solutions for residential and light commercial or industrial applications, low temperature cooling systems. Within the FP7-ALONE project, financed by the EU, the Department of Energy Engineering "S.Stecco" is responsible for the installation of an Solar Heating&Coolinf (SHC) plant in a real application at the Misericordia of Badia a Ripoli (Florence).

For the optimized design of the SHC plant a key-point have been the analysis of the building and of the already existing air-conditioning system that allowed to evaluate potentialities for the coupling of the solar plant with the specific real application. Another key-point have been the preliminary evaluation of the energy loads of the building: dynamic models have been developed in TRNBuild [1], in order to make a sensitivity analysis of loads depending on temperature, relative humidity and gains.

The last step for the optimized design was the development in TRNsys of a complete dynamic simulation model that implemented the design idea for the coupling of the SHC plant to the main building. A sensitivity analysis of the energy savings have been carried out depending on the thermodynamic conditions and on air mass-flows: the SHC plant operative ranges have been optimized in order to maximize the energy savings.

Introduction

Cooling demand is rapidly increasing in many parts of the world and the Solar cooling technologies, which use solar thermal energy provided by solar collectors to drive cooling machines can significantly contribute to a rising share of renewable heat sources in the building sector and a sustainable energy development in Europe [2].

Within the FP7-ALONE project, financed by the EU, the Department of Energy Engineering "S.Stecco" is responsible for the installation at the Misericordia of a SHC plant based on PTC collectors (12 collectors for a total area or 108 m^2) for direct steam generation (at 190°C) coupled with an ammonia-water absorption chiller (with a nominal cooling capacity of 17 kW with a COP=0,7). The solar field and the chiller are both connected to a unique component, the Energy Box: it implements all components necessary for the control and monitoring of the plant, and it has been appropriately developed and designed during the FP7-ALONE Project.

The first step of the design process have been the definition of the lay-out of the solar field, for which, a TRNsys model have been developed in order to evaluate seasonal and yearly energy production: PTC collectors will be installed in a unique row oriented with a 21° declination angle in respect to the N-S direction and the yearly energy yield is about 65106 kWh (44121 kWh during summer and 20985 kWh during winter) [3].

In parallel, a deep analysis on the existing air-conditioning have been carried out in order to evaluate potentialities for the installation of the SHC plant. The main building is made of four floors for a total area of about 700 m^2: all floors have a centralized air-conditioning system made of heat pumps connected with fan-coils that distributes the conditioned air into the rooms and a mechanical ventilation system that provides the air-exchange.

The main objective of the project is to assist the already existing air-conditioning equipment only for the basement, the ground and first floor, using the energy produced by the SHC plant for the pre-treatment of the ventilating air. The air inlets/outlets for the ventilation system are in the northern side of the building despite of the second floor, whose inlets are in the southern side, therefore it will be excluded from the coupling with the SHC.

A dynamic model have been developed in TRNBuild in order to evaluate the yearly and seasonal energy loads (sensible and latent) of the building at the Misericordia, as a function of the temperatures and relative humidity conditions. The model have been validated comparing the maximum heating loads with the potentialities of the already existing plant.

For an optimized implementation of the SHC plant with the building it was crucial to preliminary know the sensitivity of the energy savings to the operating conditions of the SHC plants. For that reason, a more complete TRNsys model that couples the two already validated dynamic models (solar field and building) have been developed in order to preliminary estimate the energy saving connected with the installation of the SHC plant, and in order to carry out a sensitivity analysis of performance as a function of the operating conditions of the plant.

Results analysis highlighted the operating condition that optimize the performance of the SHC plant.

Misericordia: Air-Conditioning System and Potentialities for the installation

The main building at the Misericordia is divided in 4 floors: the Basement (cafeteria, refectory and kitchen), the Ground and the First Floor (outpatient rooms and reception) and the Second Floor (outpatient, special medical services and gymasium).

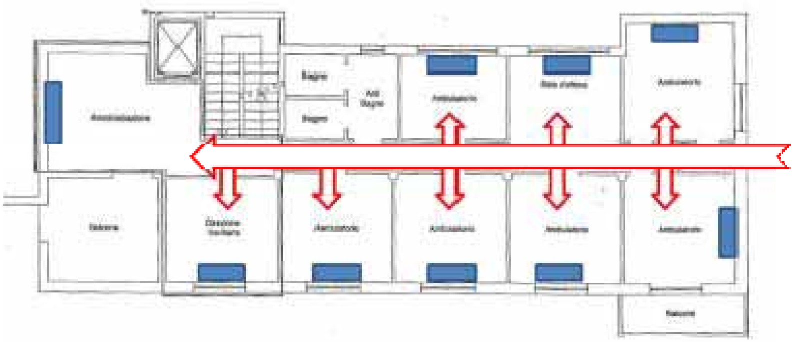

Fig. 1 – First and ground floor : Plan and Air-Conditioning system

The plan of the ground and the first floor are almost identical, as the air-conditioning system: a centralized air-conditioning system made of heat-pumps (outside of the building: 3 machines in total for the two floors) supply heating and cooling energy that is distributed/dissipated by floor standing fan-coils in the inside of the building (one for each room, as marked in blue in Fig. 1).

The air-exchange is done by a centralized mechanical ventilation system that takes the air from the outside and convey it inside the building through a canalization installed in a false ceiling (as marked in red in Fig. 1).

The Basement has a different plan (Fig. 2 - the larger area is used as Cafeteria and Refectory and the smaller one is the Kitchen) and a different air-conditioning system: one cross-to-cross air flow heat recovery system (marked with a circle in Fig. 3 and two Air Handling Units are used for the air-conditioning of the Basement (marked with a square in Fig. 3). All the equipment is installed behind a supporting wall or over a false ceiling.

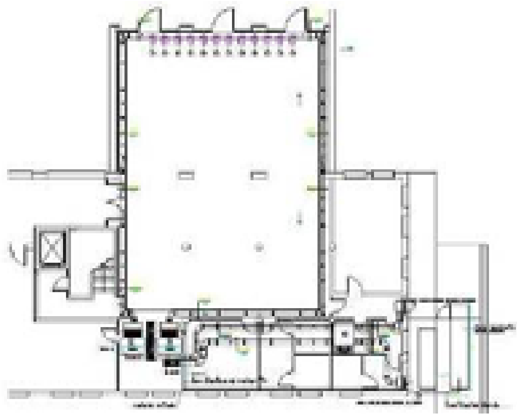

Fig. 2 – Basement : Plan

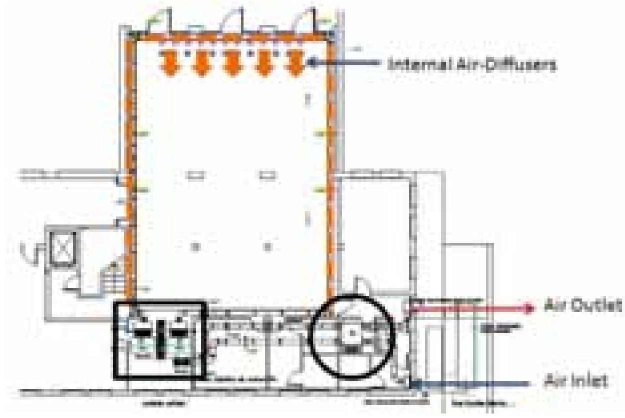

Fig. 3 - Basement : Air-Conditioning system

The functioning of the system is described in Fig. 3: the air is mechanically conveyed into the heat recovery device, where it exchanges heat with the air coming out from the inside. The pre-treated inlet air, then, pass through the air handling units where it is heated (or cooled) and humidified (or de-humidified) depending on the winter/summer season. The conditioning air, then, is distributed into the refectory/cafeteria through air-diffusers.

In the northern side of the main building there are the air intakes and outlets of the mechanical ventilation system for the basement, the ground and the first floor. The main design idea for the implementation of the SHC plant with the already existing system is to pre-treat the mechanically ventilated air through an external air handling unit, using the heating and cooling energy produced by the plant.

This solution is suitable only for the basement, the ground and the first floor, since for the second floor the air intakes/outtakes are in the southern side of the building: it wouldn't be profitable to connect the SHC plant also to the second floor, since there would have been necessary a lot of additional adaption works to the building, that would have increased the costs for the installation.

Table 1 illustrates the power potentialities of the already existing air-conditioning equipment at the Misericordia: they are surely over-estimated in relation to the real energy demand of the building during the whole year, therefore, it have been necessary to develop dynamic simulation models with

TRNBuild, in order to preliminary evaluate the hourly thermal and cooling loads of the building.

FLOORS	Heating Power	Cooling Power
	kW	kW
Basement	23.10	22.40
Ground Floor	25.00	19.50
First Floor		
TOTAL	**48.10**	**43.90**

Table 1 – Heating and cooling potentiality of the existing air-conditioning system

Modelling and Simulation : Energy Loads of the Building

Taking into consideration the installation site and the differences among the plan of each floors, two different models have been developed in order to preliminary evaluate energy loads of each floor of the building. The main features of models are listed in Table 2

MAIN FEATURES OF THE TRNSYS MODEL FOR THE MISERICORDIA		
	Ground and First Floor	Basement
N° rooms	18	1
Temperature Setpoints (Winter/Summer)	20°C/26°C	
Relative Humidity Setpoint	50%	
Ventilation	Yes (500 m^3/hour)	Yes (1000 m^3/hour)
Infiltration (1/h)	0.2 (standard on type56)	
External Shading	no	
Occupancy Profile for each zone	Yes (ISO 7730)	
Internal Gains profile	People, Computers, Lights	

Table 2 – Misericordia : Main features of the TRNsys model

Each model implements an iterative feedback control that rules the switch on/off of the heating and cooling equipment depending on the temperature inside each room and another internal controller that allow to control the relative humidity conditions inside the building.

The model also implement forcing functions that define the daily operating hours of the already existing air-conditioning equipment (from 8 to 20) and that define the season type: winter season starts on the 1st of October and ends on the 31st of March while summer starts on the 1st of April and ends on the 30th of September.

The mechanical ventilation have been designed in line with the nominal volumetric air-flow of the equipment installed at the Misericordia.

Temperature and RH set-points for the model have been defined referring to ISO 7730 [4], as for the occupancy profiles and internal gains, and a ±20% range for the relative humidity condition have been set up in order to evaluate comfort condition inside the building.

It has to be considered that gains contributes to the reduction of the heating load during winter and to the increasing of the cooling one during summer, therefore, the presented results of simulations under-estimated the cooling power/load and over-estimated the heating ones.

During simulations, no heat transfer among floors has been considered, therefore the total load of the building have been calculated as the sum of the hourly load for each floor.

Fig. 4 illustrates the daily average heating and cooling loads calculated on the functioning hours of the air-conditioning system (from 8 to 20): the heating power peaks are around 30-31 kW and cooling ones are almost 25 kW.

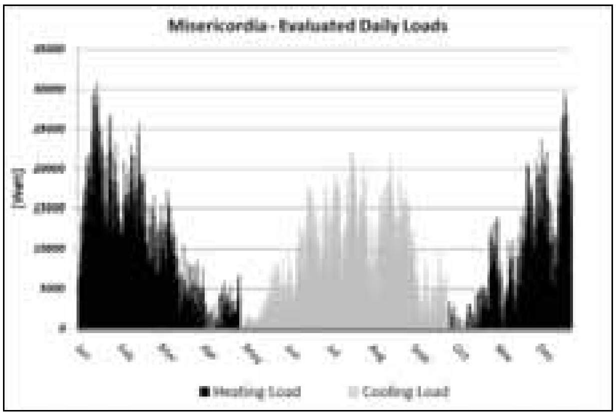

Fig. 4 – Misericordia : Hourly energy loads evaluated with TRNsys

Modelling and Simulation : SHC plant

The main design idea within the FP7-ALONE project is to assist the already existing air-conditioning equipment for the basement, the ground and first floor, using the energy produced by the SHC plant for the pre-treatment of the ventilating air, in order to reduce the loads.

The already existing mechanical ventilation system is designed to provide hourly circulation of 500 m^3 of air-flow in the ground and first floor, and 1000 m^3 in the basement, for a total amount of 2000 m^3/hour.

Starting from the model already developed for the design of the lay-out of the solar field [5], a more complete dynamic model that implemented the ammonia-water chiller and an air handling unit have been developed in order to evaluate potentiality of the SHC plant for the production of 2000 m^3/hour at specific conditions.

The operating temperature of the SHC plant have been set up at 20°C in winter and 26°C in summer, while the relative humidity set-point have been set up at 50%. The RH set-point is only a target for the SHC performance evaluation: it has to be highlighted that, during winter the air humidity ratio is assumed constant.

The SHC plant would have to provide always 2000 m^3/h to the mechanical ventilation equipment and, if the energy produced by the solar field is not enough to bring such amount of air at the required conditions, the mixing of treated air with ambient air is mandatory. For that reason a specific control logic that rules the distribution/mixing of the air into the building have been developed during the design of the plant and the developed model implement it.

AHU Energy and SHC Potentiality - Sensitivity analysis to the operating temperature at 50% RH						
	AHU - Heating			AHU - Cooling		
	18°C	20°C	22°C	22°C	24°C	26°C
Energy required by AHU [kWh/year]	8418	13583	13583	15039	10034	8883
Working hours AHU [h/year]	1711	1996	1996	911	667	456
SHC Plant Potentiality	Winter			Summer		
Treated air mass flow less than the nominal [h/year]	318	502	802	518	313	326
Time out of Comfort Conditions [h/year]	183	332	574	0	0	0

Table 3 – AHU Energy and SHC Plant potentiality : Sensitivity to the Operating temperature (50% RH)

The model evaluate hourly thermodynamic and hygrometric conditions of the ventilating air: a sensitivity analysis of the SHC potentialities have been carried out in order to analyze the performance of the system depending on the operating conditions.

Table 3 illustrates the sensitivity of the energy required by the AHU to the operating temperature, while the relative humidity set-point is set at 50% during summer: the first row shows the energy required by the AHU to pre-treat 2000 m^3/h of air at the set-point conditions while the second row highlight working hours per year for the AHU.

SHC potentiality are evaluated comparing the hourly power provided by the plant with the power required by the AHU to pre-treat 2000 m^3/h of air at set-point conditions: the third row highlight that the SHC plant is not always able to supply the required energy to the AHU.

The design idea is to treat a lower volumetric air-flow within the AHU in order to reach anyway the set-point conditions: in these conditions the treated air-flow is mixed with ambient air in order to supply anyway 2000 m^3/h to the mechanical ventilation system of the building.

Last row illustrate the capacity of the plant to respect the comfort standard requirements in terms of relative humidity.

A sensitivity analysis on performance have been carried out also on the relative humidity conditions of the AHU during summer (set-point temperature: 26°C) in order to evaluate the cooling production reliability of the SHC plant.

AHU Energy and SHC Potentiality - Summer			
Sensitivity to the Relative Humidity at 26°C			
AHU - Cooling			
	22°C	24°C	26°C
Energy required by AHU [kWh/year]	8681	5814	3071
Working hours AHU [h/year]	456	456	456
SHC Plant - Summer Potentiality			
Treated air mass flow less than the nominal [h/year]	326	171	68
Time out of Comfort Conditions [h/year]	0	0	0

Table 4 - AHU energy and SHC plant potentiality : Sensitivity to the relative humidity (at 26°C during summer)

Table 4 highlights that the decreasing of the relative humidity conditions of the treated air entails a decrease of potentiality of the SHC plant to supply the required energy to the AHU: set-point conditions are not guaranteed by the plant, it is necessary to mix the treated air with an higher ambient air-flow and for a longer time. Results also highlight that during summer, even if the SHC plant isn't able to guarantee the set-point conditions, it is able to respect the comfort standard while AHU is working.

Complete Model : Results and Conclusions

The main aims of this work are the definition of the operating thermo-hygrometric conditions that optimize the performance of the SHC plant and the development of a control logic for the AHU and for the distribution of the treated air-flow inside the building, that optimize the comfort conditions.

TRNsys model - Reference Conditions			
Parameter		SHC PLANT	BUILDING
Temperature [°C]	Winter	20	20
	Summer	26	26
RH [%]	Winter	No Set-point (constant humidity ratio)	50%
	Summer	50%	50%

Table 5 - TRNsys Complete model – Reference conditions

For that reason the model for the SHC plant have been coupled with the two models for the building's floor in order to preliminary estimate the energy savings connected with the installation of the SHC plant at the Misericordia, and in order to carry out a sensitivity analysis of performance as a function of the operating conditions of the plant.

Table 5 illustrates the set-point conditions defined for the complete models.

No heat transfer among floors has been considered: the yearly load of the building with or without the installation of the SHC plant have been calculated as the sum of the hourly load for each floor.

At the moment, no dehumidifier or humidifier is installed at the Misericordia, therefore it has been necessary to preliminary evaluate thermo-hygrometric conditions inside the building in order to check if comfort requirements are respected. Energy loads and comfort conditions have been preliminary evaluated only for the main building, and then a analysis on loads and comfort sensitivity to the relative humidity set-point for the AHU have been carried out on the complete.

The analysis of loads have been carried out in terms of yearly primary energy savings: for the conversion of the net energy into primary one, multiplication factors have been considered 2.5 for cooling energy [6], and 0.95 for heating energy.

Primary energy loads and Discomfort hours				
Only Building				
	Primary Energy Load		Discomfort hours	
RH Setpoint Ventilation	Heating [kWh/year]	Cooling [kWh/year]	Winter [h]	Summer [h]
Ambient	18183	5593	79	770
Building + SHC plant				
RH Setpoint Ventilation	Primary Energy Load		Discomfort hours	
	Heating [kWh/year]	Cooling [kWh/year]	Winter [h]	Summer [h]
40%	8279	4984	27	398
50%	8279	5123	27	463
60%	8279	5198	27	764

Table 6 – Primary energy loads and Discomfort hours: Sensitivity to the operating relative humidity of the AHU

Table 6 illustrates that the yearly primary energy load of the building is 23776 kWh (18183 kWh of primary energy for heating and 5593 kWh for cooling) while the total discomfort hours are 849 (79 during winter and 770 during summer).

The sensitivity analysis lead to the definition of the relative humidity operating set-point plant that optimize the performance of the SHC system, while it is operating at 20°C during winter and 26°C during summer. In fact, Table 6 also highlights that the most profitable solution is to drive the SHC plant and AHU equipment in order to treat the air-flow at 40% or relative humidity during summer, since at these conditions the primary energy load is the lowest (13263 kWh) and the discomfort hours are minimized (398 hours).

Misericordia - Sensitivity Analysis to Operating Temperature at RH 40%									
Primary Energy Savings					Discomfort Hours				
Operating Temperature		Summer Temperature			Operating Temperature		Summer Temperature		
		22°C	24°C	26°C			22°C	24°C	26°C
Winter Temperature	18°C	9560	9297	8955	Winter Temperature	18°C	245	312	438
		-40%	-39%	-38%					
	20°C	11118	10654	10513		20°C	232	300	425
		-47%	-46%	-44%					
	22°C	12333	12048	11708		22°C	226	294	419
		-52%	-51%	-49%					

Table 7 - Primary energy savings and Discomfort hours : Sensitivity to the operating temperature of the AHU

Starting from that, further a sensitivity analysis on operating temperature of the SHC plant and AHU have been carried out, in order to define the operating temperature ranges that optimize the system.

Table 7 highlights that with the installation of the SHC plant it is possible to save primary energy within the 38% and the 52% in respect of the primary energy load of the building, depending on the operating temperature of the AHU equipment. Also it is possible to highlight that with the installation of the SHC plant the discomfort hours are reduced to 438 down to 226.

Table 7 also illustrates that the primary energy savings are highly sensitive to the winter temperature, while they are not so dependent from the summer one: the increase of the winter temperature from 18°C to 22°C entails an increase on the primary energy savings of about the 11-12%, while the decrease of the summer temperature from 26°C to 22°C entails an increase of about the 2-3%.

On the other side, the discomfort hours are highly sensitive to the summer temperature while they are not so sensitive to the winter one: the decrease of the winter temperature from 26°C to 22°C entails a increase of comfort of about 200 hours, while the increase of the winter temperature from 18°C to 22°C entails an increase of comfort of about 20 hours.

In order to maximize the energy savings and minimize the discomfort inside the building, the operating condition for the AHU equipment connected to the SHC plant at the Misericordia are the following:

- Relative Humidity : 40%
- Winter Temperature : 22°C
- Summer Temperature : 22°C

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